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Magnetospectroscopy to 18 T of Phosphorous Donor in Silicon

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Introduction

The intentional introduction of impurity atoms into high-quality semiconductor crystals is the basis of the electronic technology that underpins much of the modern information economy. Group V atoms introduce energy states just below the conduction band of a group IV host. These shallow levels have been subject to intense study from both theoretical and experimental points of view. Here we report the far-infrared absorption magnetospectroscopy of P donor in Si to higher magnetic fields than those employed previously. The observations confirm and extend the previous work and reveal new interactions between the electron states.

Experiment

The sample used in these experiments was bulk P-doped Si (number RAL3A), 2.3 mm thick, prepared from pure Si by neutron transmutation doping at ANSTO. The P concentration was about $1 \times 10^{14} \text{ cm}^{-3}$. The sample was wedged to suppress optical interference between the front and back $\langle 111 \rangle$ faces.

Measurements were made using a Bruker I13v Fourier spectrometer equipped with globar and Hg light sources and liquid-helium-cooled Si bolometer detector. Appropriate beam splitters were employed to optimize the signal for the various spectral features examined.

Experiments at high magnetic field were carried out using an 18-T superconducting magnet. The light was conducted to the sample at field centre via a metal light pipe and a condenser cone. Measurements were made with the magnetic field parallel to the direction of light propagation (Faraday configuration) using nominally unpolarized radiation; in this geometry, $\mathbf{E} \perp \mathbf{B}$.

Results and discussion

In Fig. 1, we plot our results at 0 and 3 T so that they may be directly compared with the photo-thermal ionization spectroscopy (PTIS) data shown in Fig. 1 of Mu *et al.* [1].

The positions of the sharp transitions agree very well, but there are subtle differences in the spectra attributable to the different experimental methods and different conditions of the experiments. Our absorption lines are relatively stronger at lower energy than the PTIS lines, as expected, due to the higher-energy states being more easily (thermally) ionized in the PTIS

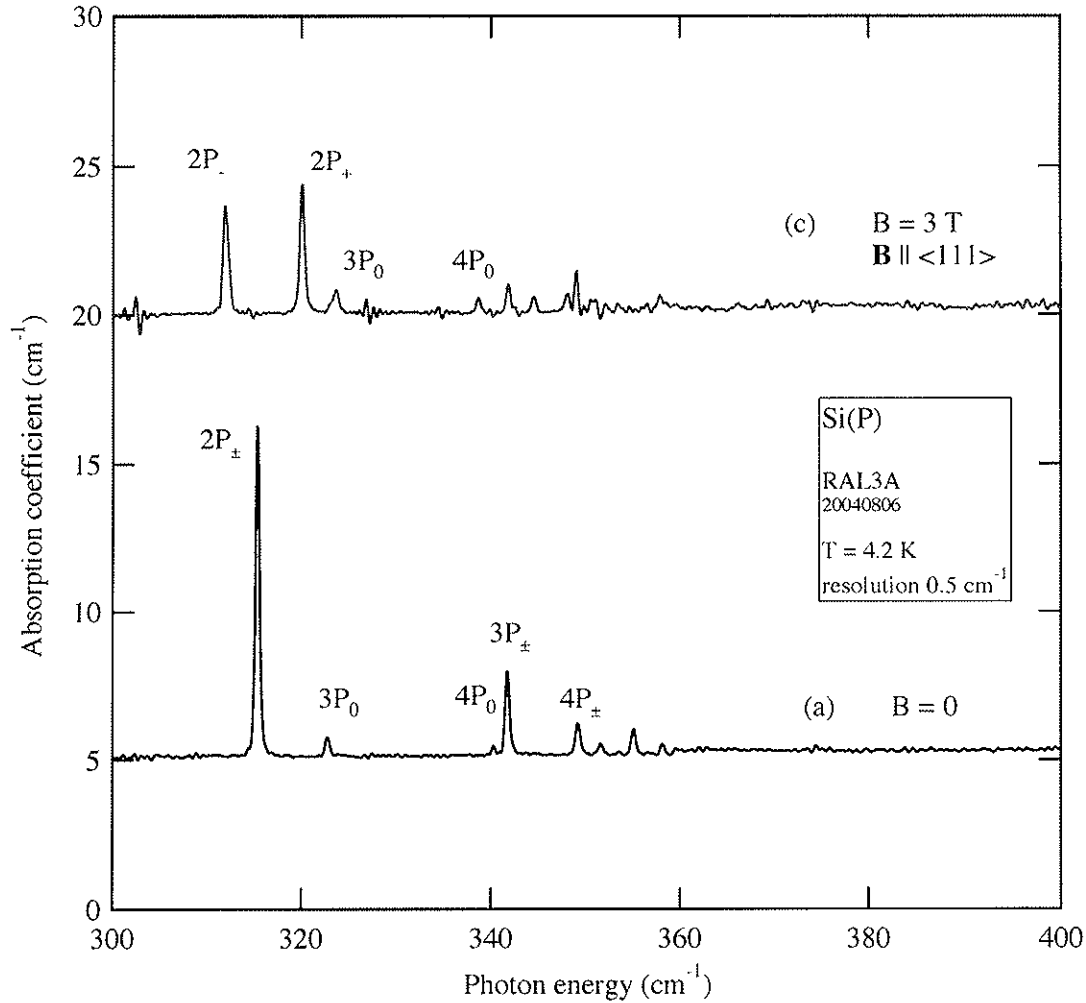


Figure 1: Experimental absorption spectrum at 4.2 K of P in Si. (a) Without magnetic field. (c) With $B = 3$ T, $\mathbf{B} \parallel \langle 111 \rangle$.

mechanism than the lower-energy states. Not needing phonons for the thermal ionization, we have been able to measure at a lower temperature, 4.2 K rather than 20 K. We resolve, for example, the $4P_0$ line at zero field, which appears only as a shoulder on the strong $3P_{\pm}$ transition in the earlier data. Furthermore, the absolute oscillator strength is readily given by the absorption lines, but is not obtained directly from PTIS.

Fig. 2 presents the spectra from 0 to 18 T in 1 T steps. The spectra are consistent with, but greatly expand in field range, the data given by Shen *et al.* [2] in their Fig. 1 to 10 T.

The dependence of some of the principal lines with field is presented in Fig. 3. (In this figure, the lines are polynomial fits.) Compared with the earlier work [2], it is seen that some new interactions and anti-crossing behaviour arises. For example, at ~ 10 T a $2P_{+}$ -like state, which has emerged from the zero-field $3P_0$ state, may be tracked through a strong interaction with a $3P_{-}$ -like state, which has emerged from the zero-field $4P_0$ state. A detailed analysis of the variation of the transition energies with field, as well as of the variation of the intensities and the line widths with field, is now in progress. Combined with new calculations of the wave-function mixing, further insight is anticipated into the quantum interactions in this system and the nature of hybridized Zeeman states in general.

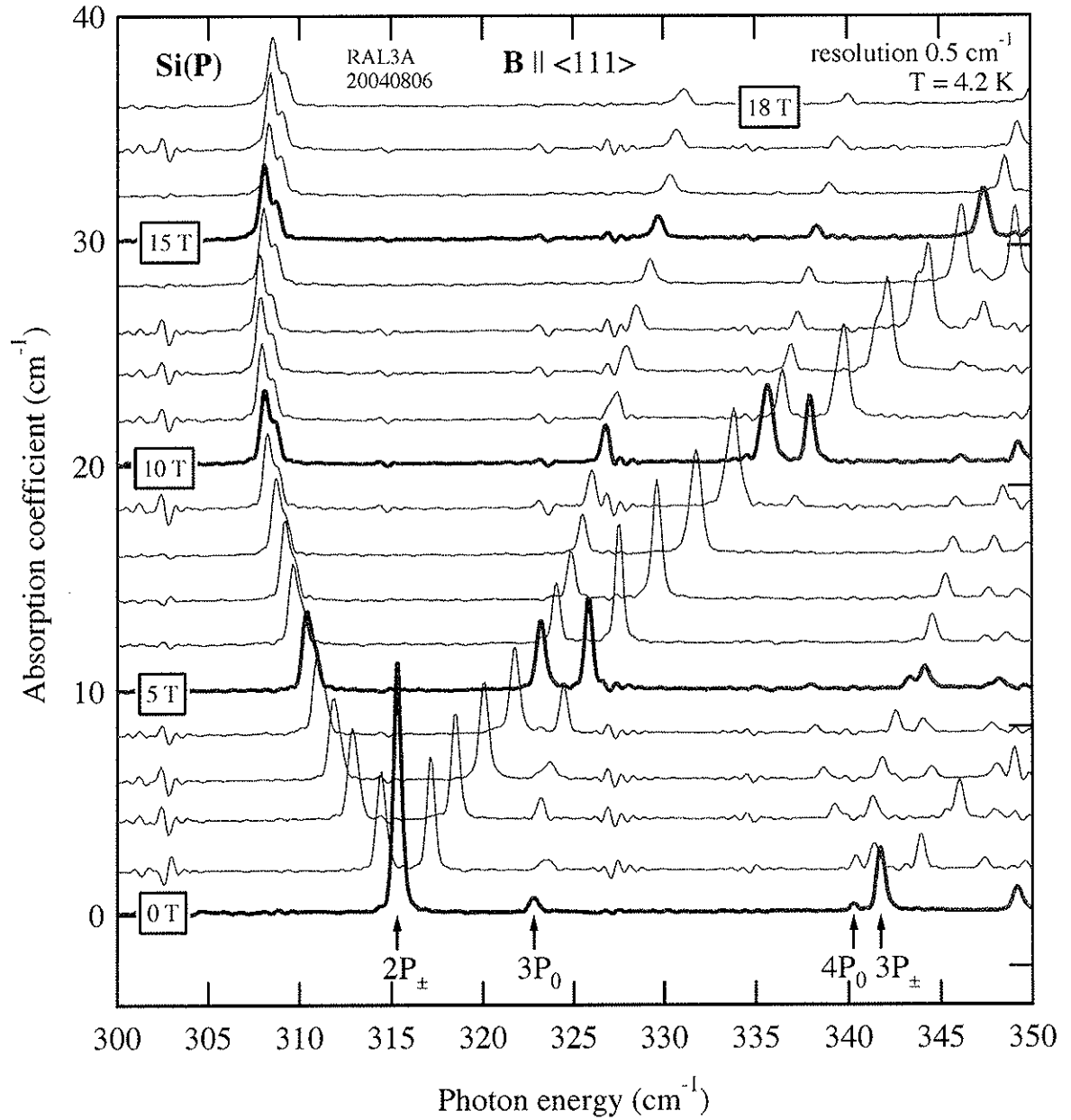


Figure 2: Experimental absorption spectrum at 4.2 K of P in Si in magnetic fields of 0 (bottom) to 18 (top) T in 1 T steps for $\mathbf{B} \parallel \langle 111 \rangle$.

Conclusion

Absorption spectroscopy provides additional information to that provided by PTIS for P donor in Si and, moreover, has been carried out now to much higher magnetic fields. Strong hybridisation of states is observed, notably the $2P_+$ -like state interacting successively with the zero-field $3P_0$ and $3P_-$ states at about 5 and 10 T, respectively.

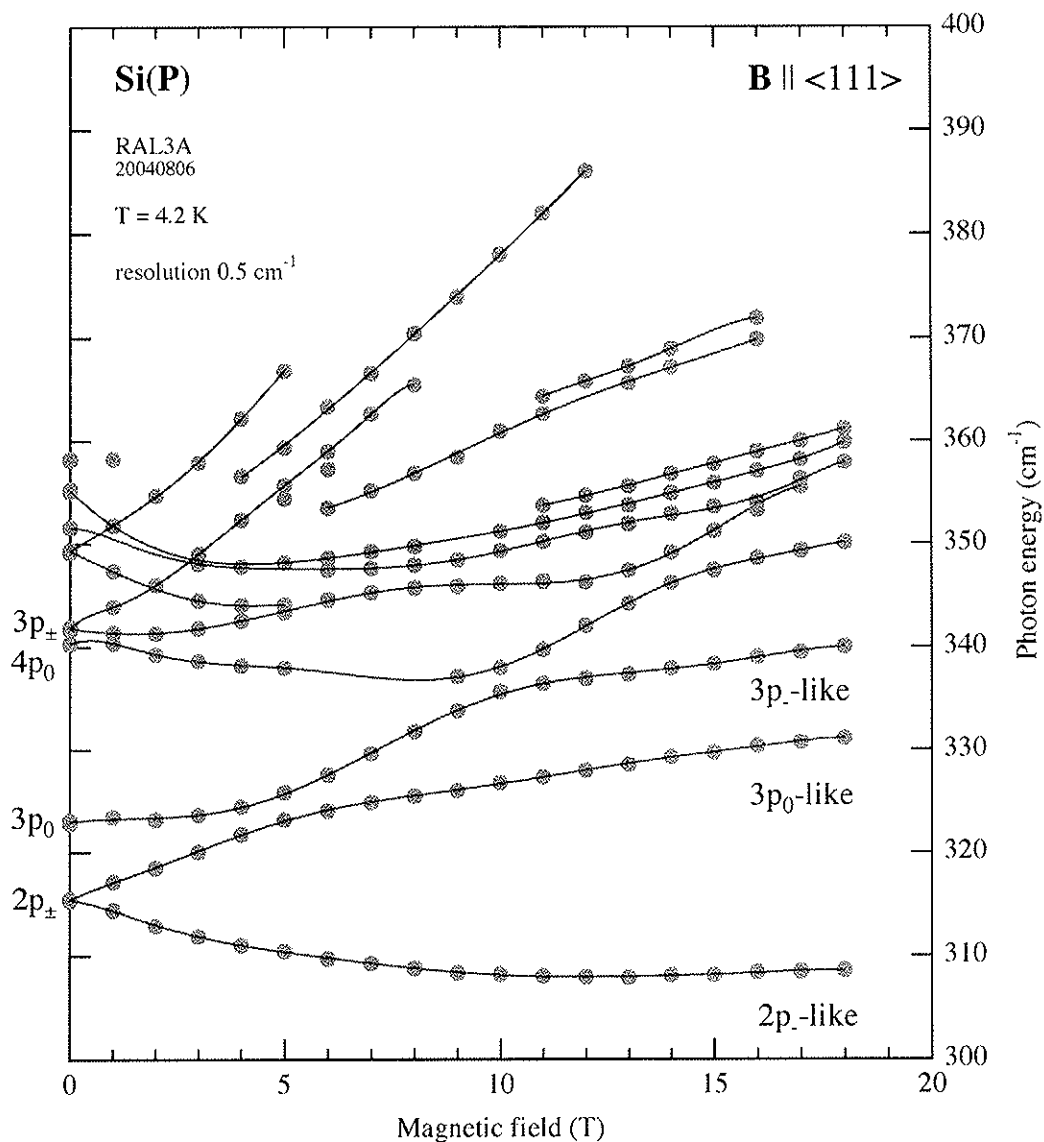


Figure 3: Splitting and shifting of some of the principal transitions of P in Si with field for $B \parallel \langle 111 \rangle$.

Acknowledgments

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